LLNL-TR-435631

LAWRENCE LIVERMORE NATIONAL LABORATORY

Fast Ignition Target Compression Campaign

P. Patel, P. Amendt, D. Clark, M. Tabak, D. Meeker, B. Lasinski, H. Shay, D. Ho, D. Strozzi, D. Larson, L. Divol, A. Kemp, M. Key

June 14, 2010

Disclaimer

This work performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

Fast Ignition Target Compression Campaign

P.I.: Pravesh Patel

Target Design: Peter Amendt, Dan Clark, Max Tabak, Don Meeker, Barbara Lasinski, Hank Shay, Darwin Ho, David Strozzi, David Larson, Laurent Divol, Andreas Kemp, Mike Key

Experiments: Sebastien Le Pape, Riccardo Tommasini, Andrew Mackinnon

Collaborators: Rich Stephens (GA), Wolfgang Theobald (LLE), Peter Norreys (RAL), Farhat Beg (UCSD)

Purpose/Goal:

The successful demonstration of ignition on the NIF will be a transforming event for inertial fusion energy (IFE). The first ignition campaign on the NIF will employ the central hot spot (CHS) inertial confinement fusion (ICF) scheme, with expected target gains of 15-20. The next step for IFE will be the development of advanced high gain targets with gains>100 that are attractive for commercial reactor design. A broad class of high gain ignition targets are based on the concept of fast ignition, in which the separation of the two phases of fuel compression and heating enable a more energetically favorable implosion, resulting in higher yield and gain [Tabak, 1994; Atzeni, 1999]. In fast ignition, the fuel is first compressed to a uniform high density, and then an external energy source (such as a relativistic intensity laser-produced electron beam) is injected to rapidly heat a small region of fuel to high temperature, initiating fusion and propagating burn. The leading approach to fast ignition uses a hollow cone inserted into the capsule, which provides a clear path through the surrounding fuel for the ignitor pulse to reach the cone tip and excite an energetic electron beam close to the compressed core.

Whilst considerable attention has been paid to the ultraintense-laser-interaction and beam-plasma physics associated with the heating phase, relatively little attention has been devoted to the hydrodynamics of fast ignition implosions. The design challenge is formidable—a fast ignition implosion must assemble a uniformly high density, high ρR (areal density) fuel configuration in close proximity to the cone tip whilst maintaining the structural integrity of the cone and avoiding mix of the cone material with the DT fuel, which would reduce gain. We have developed 1-D spherical capsule, and 2-D integrated hohlraum and spherical capsule, target designs that meet peak density of ρ~300 g/cm^3 and ρR>2 g/cm^2 requirements. Two candidate pulse shapes have been explored—a novel single shock pulse, and a more conventional four-shock design. These implosion designs are used as the basis for 2-D cone-in-shell calculations wherein parameters such as drive asymmetry and cone angle are varied to optimize the final fuel configuration.

We propose an experimental campaign on the NIF to validate key elements of the fast ignition target design. Experimental measurements will provide feedback for refinement of the target design. In lieu of the cryogenic DT target, which requires ongoing target fabrication R&D, the initial experiments will use a surrogate target design consisting of a cryogenic H/He gas-filled hohlraum with CH capsule. In the first year we will validate hohlraum energetics, symmetry tuning, and measure peak ρR with spherical capsule implosions, for each of our two candidate pulse shapes, with the aim of down selecting to a preferred drive pulse. In the second year we will progress to cone-in-shell implosions, using x-ray radiography and Streaked Optical Pyrometry (SOP) inside the cone to measure and optimize the ρR and shape of the compressed core and the timing between optimum fuel compression and shock breakout in the cone. Our goal is to establish an indirect drive fast ignition compression platform that will demonstrate the validity of the implosion scheme, and provide a basis for future core heating experiments using the 10 kJ, 10 ps Advanced Radiographic Capability (ARC) short-pulse NIF beam line.

Scientific Questions to be addressed:

The proposed experiments will, for the first time, address the major issues for isochoric fuel assembly of a fast ignition target at full hydrodynamic scale (i.e., ignition-scale targets). In contrast to a conventional isobaric CHS implosion, a fast ignition implosion is required to assemble a near-uniform density, or isochoric, compressed core with no central hot spot. We have developed two different compression schemes that each offer potential advantages. Figure 1 shows a comparison of the two schemes for a baseline DT target using 500-600 kJ drive energy.

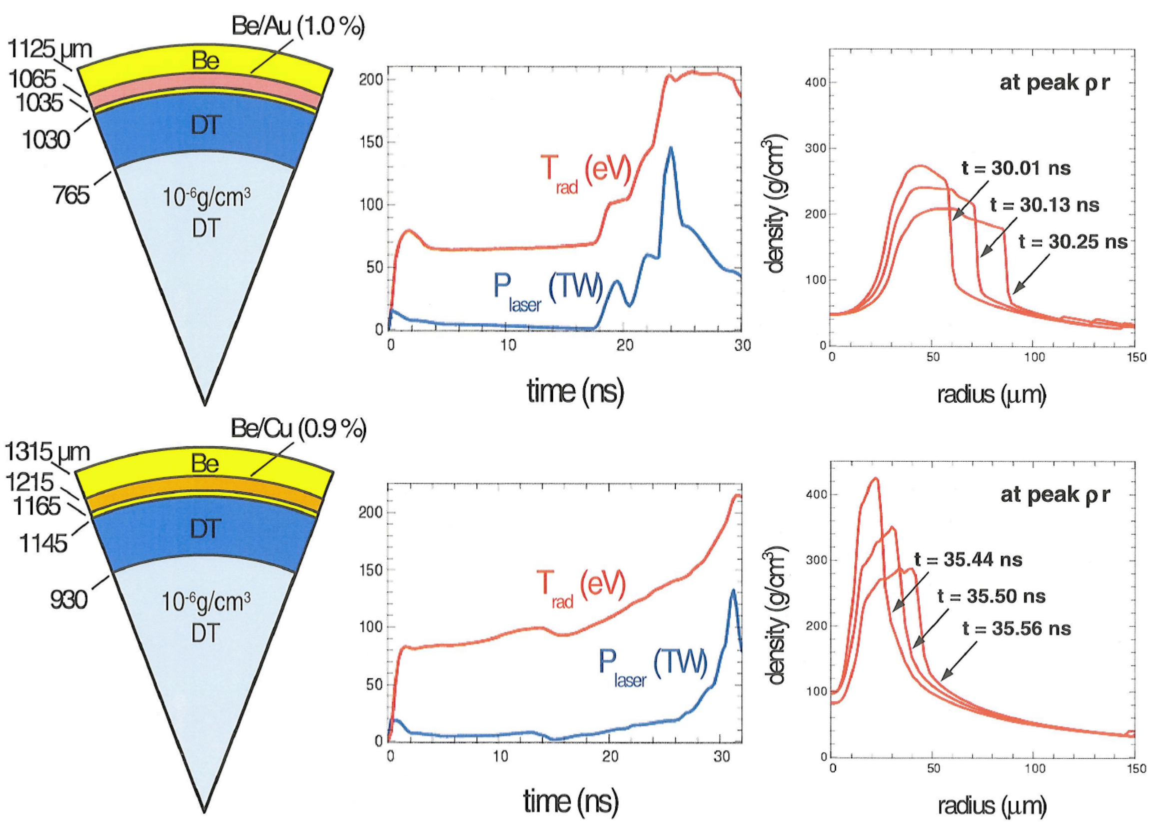


Fig. 1. Capsule design, laser and radiation drive history, and density profiles for four-shock design (top) and single shock design (bottom).

The single-shock capsule is based on a novel self-similar implosion design, which exhibits the property of generating a quasi-isochoric fuel assembly with nearly zero hot spot volume [Clark, 2007]. It employs a standard Cu dopant in the ablator to protect the cone from hard x-ray preheat that would otherwise cause ablation from the cone surface and mixing with the DT fuel. A risk for this design is the possible difficulty of tuning the capsule implosion. The more conventional four-shock design has the advantage of leveraging a shock timing methodology developed in the National Ignition Campaign (NIC). However, the final assembled fuel state is not as optimized as in the single-shock case, and the requirements on ablator dopant material and concentration are more stressful. For the 500-600 kJ designs shown in Fig. 1 the peak areal densities are 1.7 g/cm^2 and 1.5 g/cm^2 for the single-shock and multi-shock cases, respectively.

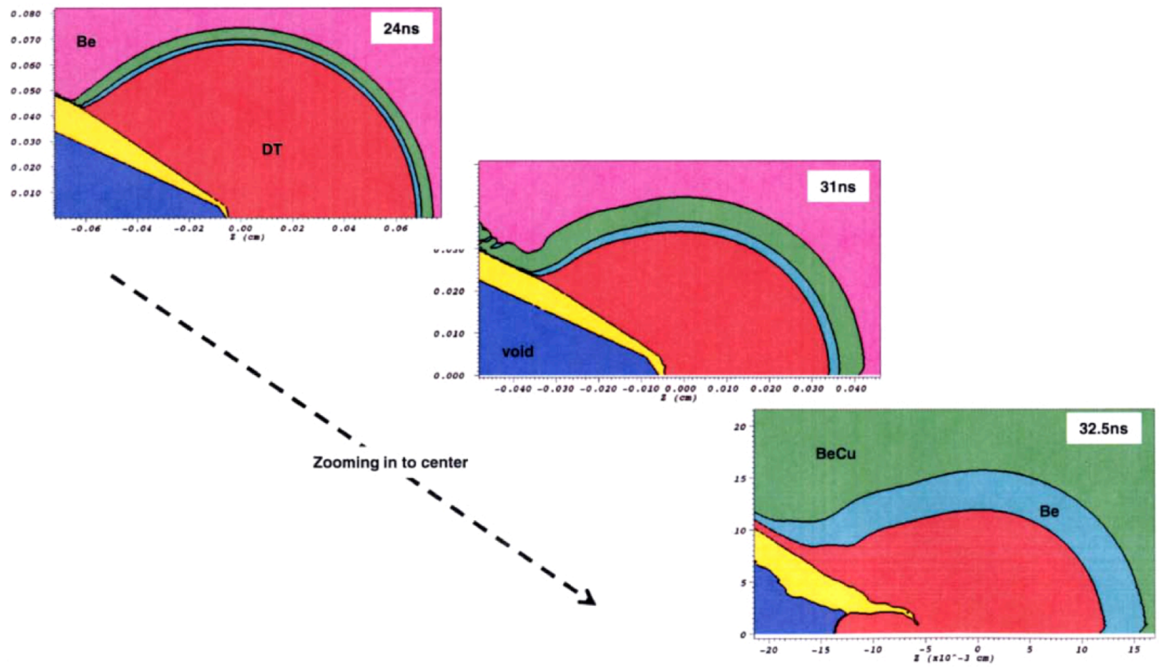


Fig. 2. HYDRA simulation of a cone-in-shell target driven with single-shock pulse shape. Near-spherical compression is maintained over a large fraction of the shell surface. Close to stagnation we observe shock breakout on the inner surface of the cone walls and an axial DT plasma jet penetrating the cone tip.

Using the 1-D compression designs we have begun a study of 2-D cone-in-shell implosions with the LASNEX and HYDRA radiation-hydrodynamics codes. A 2-D integrated hohlraum calculation provides the frequency dependent radiation source in these simulations. Figure 2 shows an example of a HYDRA simulation of a Au cone/DT capsule driven with the single-shock compression scheme. These simulations bring to light a number of challenging issues, including (i) maintaining close to 1-D performance; (ii) minimizing the cone tip to core separation distance; (iii) suppressing formation of an axial jet near peak stagnation directed toward and destroying the cone tip; (iv) correctly treating the sliding shell/cone wall interface; (v) minimizing pre-heat, ablation, and mixing of the cone wall material with the fuel; and (vi) preventing shock breakout at the inner surface of cone wall prior to arrival of ignitor pulse. In our design study we are exploring the effects of cone angle, tip thickness, initial distance of cone tip to capsule center, cone material (Au or high density carbon), Be tamping of Au cone, and asymmetric drive. Burn calculations, at or near peak compression, provide an estimate of the maximum achievable yield and gain. In parallel, we perform particle-in-cell (PIC) and hybrid-PIC electron transport modeling of the ignitor beam to iterate on finding an optimum integrated fast ignition target design. We expect to continue to address these issues and continually refine out integrated design throughout FY10/11 in preparation for cone-in-shell experiments in FY12.

Proposed experimental method:

We request a total of 10 shots in FY11, and 10 shots in FY12:

FY11 shot plan

Goal	*Diagnostics*	#
Hohlraum energetics—validate radiation drive history and LPI; measure M-L band	FABS, NBI, GXD, DANTE, M-L band measurement with SXI, streaked self-emission	2
Symmetry tuning with gas-filled capsules—measure & optimize shape through self-emission; measure ρR with X-ray radiography	As above + X-ray radiography using either thermal radiography (Zn @ 9keV, pinhole with area BL, 40 kJ in BL) or Compton radiography (10 µm, Au wire, 2 quads 88 ps)	4
Measure ρR of voided capsules (primary surrogate capsule design)	FABS, NBI, DANTE, M-L band, X-ray radiography	2
Radiograph fuel configuration around cone tip with cone-in-shell target	As above	2

FY12 shot plan

Goal	*Diagnostics*	#
Validate shock breakout time in cone versus peak ρR	SOP in cone, DANTE, M-L band	1
Contingency—if shock breakout time too early then change cone tip thickness or change standoff distance to capsule center	As above	1
Investigate cone blow off and mix with varying cone structures and dopant concentration—Au/Be, high density carbon (HDC) cones	X-ray radiography, DANTE, M-L band	4
Symmetry tuning to obtain spherical compression with cone-in-shell target	X-ray radiography, DANTE, M-L band, FABS, NBI	4

We are able to extensively leverage techniques developed by NIC for indirect-drive hohlraum and capsule tuning. In FY11 our first targets use standard NIC Au hohlraums with spherical gas-filled CH capsules for hohlraum energetics tuning. In addition to the standard NIC hohlraum diagnostics we will measure the Au M- and L-band radiation flux using an absolutely calibrated image plate (IP) on either the SXI or central channel of DANTE. This measurement is required to determine the optimum level of dopant required in the ablator for integrated cone-in-shell targets. Symmetry tuning will be achieved through adjusting power balance between inner and outer cone beams. Once adequate symmetry is obtained the gas-filled capsules will be substituted with the primary voided CH surrogate capsule. The imploded core shape and ρR will be measured through multi-frame X-ray radiography. We will select from two options: (i) thermal radiography using a large area Zn He-alpha (~9 KeV) backlighter with pinhole imaging and GXD that uses 2 quads with a total of 40 kJ energy in 2 ns on the backlighter; or (ii) Compton radiography with 10 μm diameter Au wires irradiated with 2 quads at 88 ps. These techniques are being developed through other campaigns on NIF. Finally, radiographs will be obtained with cone-in-shell targets to make an initial assessment of the impact of the cone on implosion symmetry. At this stage we aim to down select to a preferred implosion scheme based on an assessment of design and experiments to date.

In FY12 we will optimize the capsule implosion in the presence of the re-entrant cone. One of the design challenges in FY10/11 will be to develop an efficient tuning methodology for the cone-in-shell target. Streaked Optical Pyrometry (SOP) will be employed along the cone axis on some shots to verify the relative timing between peak compression and shock breakout on the inside cone surface. This technique has been used successfully in direct-drive cone-in-shell implosions on OMEGA [Stoeckl, 2007]. Multi-frame X-ray radiography will be the primary diagnostic for measuring the areal density and shape of the compressed fuel configuration, separation distance from the cone tip, and the degree of cone blow off, if any, due to hard x-ray preheat of the cone.

Degree to which the experiment is uniquely suited to NIF

Fast ignition implosions with re-entrant cone targets have been studied on the GEKKO XII and OMEGA compression facilities using laser drive energies of 2 to 20 kJ [Kodama, 2006; Theobald, 2009]. The highest ρR achieved in these implosions is ~0.2 g/cm^2, approximately an order of magnitude below that required for ignition. Ignition scale implosions with 500 kJ to 1 MJ laser drive clearly present a new set of challenges. The NIF will enable for the first time compression experiments at the full hydrodynamic scale required for high gain fast ignition. The experiments proposed here are the first step in developing an indirect-drive fast ignition target at full ignition scale.

References

S. Atzeni, Phys. Plasmas **6,** 3316 (1999)
D.S. Clark and M. Tabak, Nucl. Fusion **47,** 1147 (2007)
R. Kodama et al., Fusion Sci. Technol. **49,** 316 (2006)
C. Stoeckl et al., Phys. Plasmas **14,** 112702 (2007)
M. Tabak et al., Phys. Plasmas **1,** 1626 (1994)
W. Theobald et al., Plasma Phys. Control. Fusion **51**, 124052 (2009)

PI name: *(Patel, Pravesh)* **Proposal title:** *(Fast Ignition Target Compression)*

Instructions

The National Ignition Facility

1. This template is designed to gather basic facility information regarding experiments proposed under the FY2010 NIF facility time call.

2. The template is broken into 5 sections:
    a) Summary of proposed experiment: Desired platform (if known), NIF shots requested, brief campaign description, sketch of experimental configuration
    b) Diagnostic requirements
    c) Laser requirements
    d) Target requirements
    e) Other requirements

3. Please fill out each section and keep your answers brief. The NIF team will request additional information as needed from the Principal Investigators. Please attach additional pages to any section as needed.

4. Further information on the facility and the NIF call may be found at: https://lasers.llnl.gov/for_users/experimental_capabilities/

5. Thank you for your assistance, and please contact the NIF User Office if you have questions.

PI name: *(Patel, Pravesh)* **Proposal title:** *(Fast Ignition Target Compression)*

Summary of proposed experiment (Page 1 of 3)

The National Ignition Facility

• Desired platform (If known): Hohlraum Energetics; Streaked Radiography

• Number of shots requested: Please fill out table below indicating number of "good data" shots requested each year. Do not add in additional shots to account for contingency, experimental problems, etc; NIF staff will consider this in planning evaluation

Summary Shot Table	*FY2010*	*FY2011*	*FY2012*	Comments
Total shots		*10*	*10*	*(Fill in if desired)*

PI name: *(Patel, Pravesh)* Proposal title: (*Fast Ignition Target Compression)*

Summary of proposed experiment (Page 2 of 3)

The National Ignition Facility

• Brief campaign description

Physics goal: (first year) Down select the optimum drive for Fast Ignition Capsule, measure ρ*r of the compressed capsule. (second year) Investigate cone in shell geometry.

2 shots : energetic shot: main goal measure LPI
Diagnostics: FASBS+NBI+GXD+DANTE+ M-L band measurement central DANTE or SXI +Shock flash measurement streak self emission
4 shots : symmetry tuning: main goal measure shape of the compressed capsule + measure ρ*r using X ray radiography.
Diagnostics: same as above + x ray radiography using GXD (90, 78)
2 shot : main goal measure ρ*r using X ray radiography on empty shells.
Diagnostics: LPI diagnostics+ GXD thermal radiography (ZN @ 9 Kev, area BL + pinhole, about 40 KJ in BL), or compton radiography (10 μm gold wire irradiated by 2 quads, 88 ps, 75J)
2 shots: main goal investigate survival of the cone.
Diagnostics: X ray radiography of cone in shell + L-M band measurement +LPI measurement

second year: Study cone survival and symmetry of the compression with a cone/shell target
Measure shock breakout time at the cone tip using SOP and blow off using X ray radiography.

1 shot: check the shock breakout time in the cone versus the peak ρr
Diagnostics: SOP in the cone+DANTE +L-M band measurement
1 shot if breakout time too early change the thickness of the tip/ or change the standoff distance of the cone
Diagnostics: SOP +DANTE +L-M band measurement
4 shots to investigate cone blow off with various cone structure CH/AU, Au/Be, HDC
Diagnostics: X ray radiography +DANTE-L-M band measurement (need to investigate if X ray radiography is suitable for HDC)
4 shots: achieve spherical compression with cone/shell target
Diagnostics: FASBS+NBI+GXD+DANTE+ M-L band measurement central DANTE

Summary of proposed experiment (Page 3 of 3)

- **Sketch of experimental configuration: Pls. provide a simple sketch of the experimental configuration below. Include orientation of target, laser and any backlighter beams, diagnostic sightlines, etc. If configuration is identical to an existing platform so indicate. For further information on existing platforms and chamber geometry see the NIF website:**
https://lasers.llnl.gov/for_users/experimental_capabilities/index.php

Hohlraum energetic type of shots: similar to the NIC shots with 192 beams and dedicated pulse shape (fast ignition single shock and four shocks drive).

Streaked radiography platform: Similar to NIC with 184 beams dedicated to the hohlraum and 8 beams to the backlighter foil. GXD will be used with the appropriate pinhole pattern. If compton radiography is used, beams on the backlighter will be 88 ps long with 75 J. if thermal radiography is used, beams will be 2 ns long, with 5 kJ in each beam.

PI name: *(Patel, Pravesh)* **Proposal title:** (*Fast Ignition Target Compression)*

Diagnostic requirements

The National Ignition Facility

- Please refer to the diagnostic list on NIF user website:
  https://lasers.llnl.gov/for_users/experimental_capabilities/diagnostics.php
- List below NIF diagnostics required for your experiment (along with a short summary description of required spatial, temporal, and spectral resolution) *or* describe what you wish to observe, and NIF staff will match to available diagnostics.

SXI lower 25 micron pinhole
SXI upper 25 micron pinhole
SXB-d
Dante 1
Dante 2
FASB 31 B
FABS 36B
NBI 36B
NBI 31B
GXD 1/GXD2 10 micron pinhole when used to look at the self emission of the compressed capsule
SOP
nTof

•A different pinhole pattern is going to be used if the thermal radiography is use, DIM 90,78 will be used

PI name: *(Patel, Pravesh)* Proposal title: (*Fast Ignition Target Compression)*

Laser requirements (1 of 2)

The National Ignition Facility

Laser Parameter	Value
1) Platform to be used	*Hohlraum energetic*
2) Number of beams required	*192*
3) 3ω energy desired per beam (Maximum allowed: 3 kJ (2nsec square); for pulses other than 2nsec square provide plot of desired power vs. time on next page. NIF User Office will inform users if energy requirements exceed allowable.)	*Fill in*
4) Peak power per beam (350 TW maximum total peak power for shaped, ignition-like pulses)	*0.460*
5) Pulse shape (up to 20 nsec duration) (Options: Square, impulse (88 psec), or shaped; provide plot of desired power vs. time for shaped pulse on next page)	*shaped*
6) SSD bandwidth (options- 45 to 90 GHz, 45 GHz default)	*45 GHz (modify if desired)*
7) Focal spot size (~250-μm (unconditioned) or ~1-mm (conditioned))	*1-mm*
9) Delays between beams (up to 10 nsec-all pulses in a quad must have same delay)	*Specify if desired*
10) Backlighter beam energy, pulse duration	*Specify if desired*
11) Other specifications	*Specify if desired*

PI name: *(Patel, Pravesh)* Proposal title: (*Fast Ignition Target Compression)*

Laser requirements (1 of 2)

The National Ignition Facility

Laser Parameter	Value
1) Platform to be used	***Hohlraum energetic***
2) Number of beams required	***192***
3) 3ω energy desired per beam (Maximum allowed: 3 kJ (2nsec square); for pulses other than 2nsec square provide plot of desired power vs. time on next page. NIF User Office will inform users if energy requirements exceed allowable.)	***Fill in***
4) Peak power per beam (350 TW maximum total peak power for shaped, ignition-like pulses)	***0.5***
5) Pulse shape (up to 20 nsec duration) (Options: Square, impulse (88 psec), or shaped; provide plot of desired power vs. time for shaped pulse on next page)	***shaped***
6) SSD bandwidth (options- 45 to 90 GHz, 45 GHz default)	***45 GHz (modify if desired)***
7) Focal spot size (~250-μm (unconditioned) or ~1-mm (conditioned))	***1-mm***
9) Delays between beams (up to 10 nsec-all pulses in a quad must have same delay)	***Specify if desired***
10) Backlighter beam energy, pulse duration	***Specify if desired***
11) Other specifications	***Specify if desired***

PI name: *(Patel, Pravesh)* **Proposal title:** *(Fast Ignition Target Compression)*

Laser requirements (1 of 2)

The National Ignition Facility

Laser Parameter	Value
1) Platform to be used	*X ray radiography*
2) Number of beams required	*184*
3) 3ω energy desired per beam (Maximum allowed: 3 kJ (2nsec square); for pulses other than 2nsec square provide plot of desired power vs. time on next page. NIF User Office will inform users if energy requirements exceed allowable.)	*Fill in*
4) Peak power per beam (350 TW maximum total peak power for shaped, ignition-like pulses)	*0.5*
5) Pulse shape (up to 20 nsec duration) (Options: Square, impulse (88 psec), or shaped; provide plot of desired power vs. time for shaped pulse on next page)	*shaped*
6) SSD bandwidth (options- 45 to 90 GHz, 45 GHz default)	*45 GHz (modify if desired)*
7) Focal spot size (~250-μm (unconditioned) or ~1-mm (conditioned))	*1-mm*
9) Delays between beams (up to 10 nsec-all pulses in a quad must have same delay)	*Specify if desired*
10) Backlighter beam energy, pulse duration	*8, 5 kJ, 2 ns square pulse*
11) Other specifications	*Specify if desired*

PI name: *(Patel, Pravesh)* Proposal title: (*Fast Ignition Target Compression)*

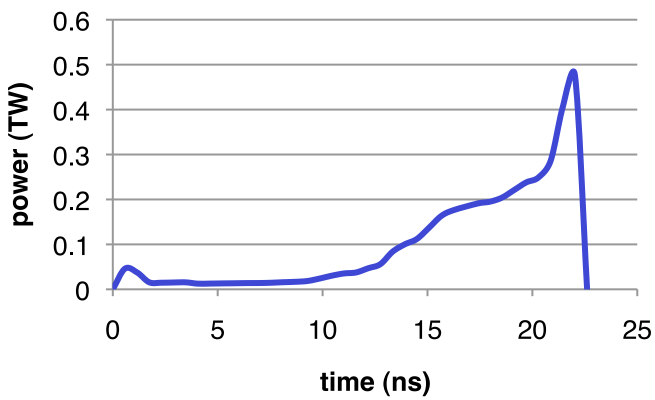
Laser requirements (1 of 2)

The National Ignition Facility

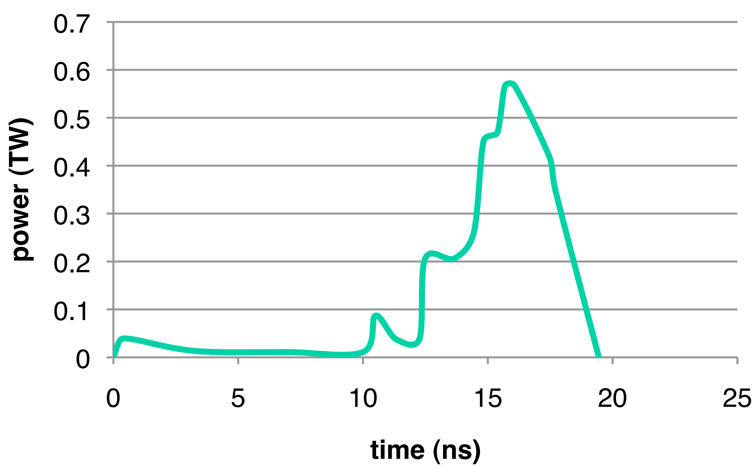
Laser Parameter	Value
1) Platform to be used	*X ray radiography*
2) Number of beams required	*184*
3) 3ω energy desired per beam (Maximum allowed: 3 kJ (2nsec square); for pulses other than 2nsec square provide plot of desired power vs. time on next page. NIF User Office will inform users if energy requirements exceed allowable.)	*Fill in*
4) Peak power per beam (350 TW maximum total peak power for shaped, ignition-like pulses)	*0.5*
5) Pulse shape (up to 20 nsec duration) (Options: Square, impulse (88 psec), or shaped; provide plot of desired power vs. time for shaped pulse on next page)	*shaped*
6) SSD bandwidth (options- 45 to 90 GHz, 45 GHz default)	*45 GHz (modify if desired)*
7) Focal spot size (~250-μm (unconditioned) or ~1-mm (conditioned))	*1-mm*
9) Delays between beams (up to 10 nsec-all pulses in a quad must have same delay)	*Specify if desired*
10) Backlighter beam energy, pulse duration	*8, 75 J, 88 ps*
11) Other specifications	*Specify if desired*

Laser requirements (2 of 2)

For shaped pulses, sketch desired power vs. time below:



Single-shock drive



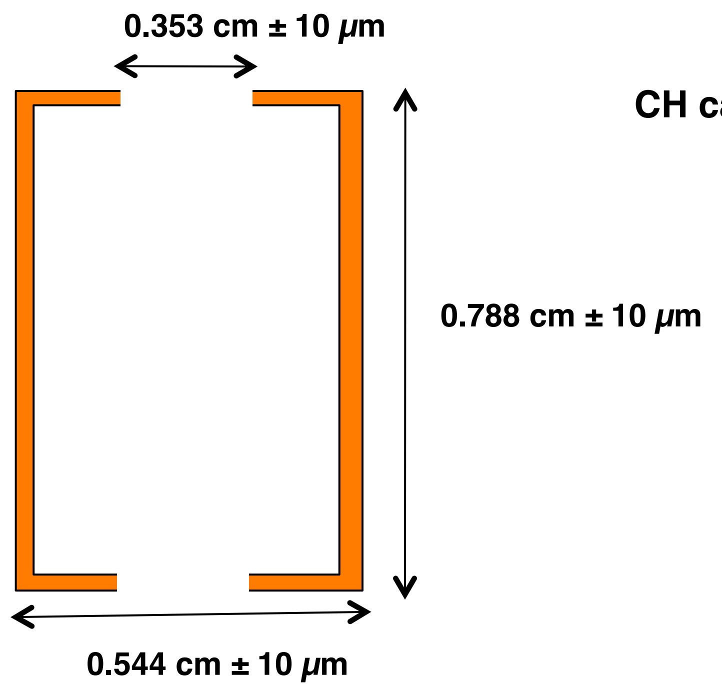
Four-shock drive

PI name: *(Patel, Pravesh)* Proposal title: (*Fast Ignition Target Compression)*

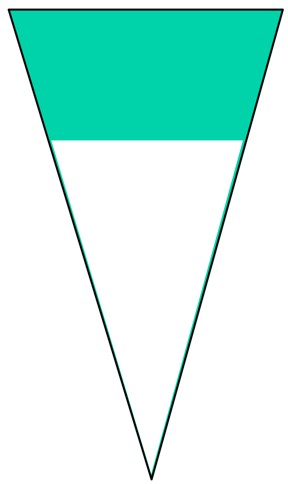
Target requirements (1 page per target type)

- **List target types required (example: drive measurement; diagnostic test; data acquisition target)**

Hohlraum : Au with He fillm capsule CH with DHe3 fill



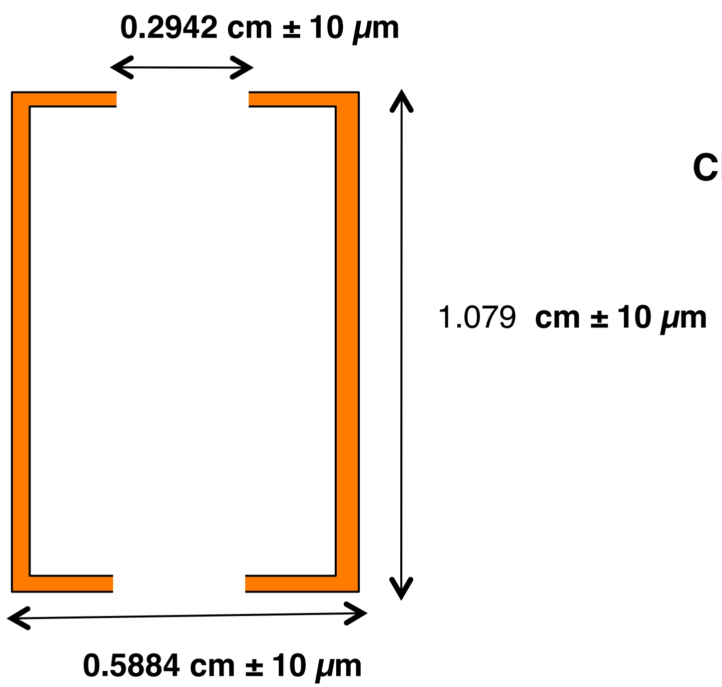
CH capsule 218 μm ± 5 μm thick, DHe3 fill



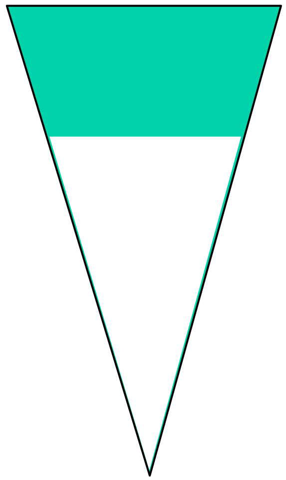
Target requirements (1 page per target type)

- **List target types required (example: drive measurement; diagnostic test; data acquisition target)**

Hohlraum : Au with He fill capsule CH with DHe3 fill



CH capsule 176 μm ± 5 μm thick, DHe3 fill



Target requirements (1 page per target type)

The National Ignition Facility

- **List target types required (example: drive measurement; diagnostic test; data acquisition target)**

Backlighter :

Cu or Zn foil for thermal radiography 25 microns thick, 2x2 mm

10 microns gold wire for compton radiography embedded in a 2x2 mm Ch foils

Other requirements

The National Ignition Facility

- **Indicate other requirements (electrical, vacuum,…) for your proposed experiment. For any items to be introduced into the target chamber not mentioned to this point, please list *all* materials to be used.**